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Surveys of Soviet-Bloc Scientific and Technical Literature

MIXING OF CONCENTRIC HIGH-VELOCITY AIRSTREAMS

Compilation of Abstracts

(Report No. 1 in this series)

Aerospace Technology Division
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FOREWORD

This report, prepared in response to ATD Work Assignment No. 60, is the first in a series dealing with published Soviet research on the subject of the mixing of concentric high-velocity airstreams. It consists of abstracts of articles selected from Soviet open literature available at the Aerospace Technology Division and the Library of Congress, and covers the period from January 1962 through June 1963. Additional reports will cover the years 1958—1961, and will also include any additional Soviet research in the field.

MIXING OF CONCENTRIC HIGH-VELOCITY AIRSTREAMS

1. Aslanov, S. K. Supersonic flow of a gas from an unsymmetrical vessel of finite width at maximum rate of flow. Izvestiya vysshikh uchebnykh zavedeniy. Aviatsionnaya tekhnika, no. 2, 1962, 3-7.

The supersonic discharge of an ideal, adiabatically compressible gas from an unsymmetrical vessel with parallel flat walls has been investigated at the Department of Theoretical Mechanics and Hydro-Aerodynamics of the Saratov State University. It was assumed that the pressure drop inside and outside the vessel was very large and that a maximum gas flow was thus ensured. A diagram of the vessel used in the investigation is shown in Fig. 1.

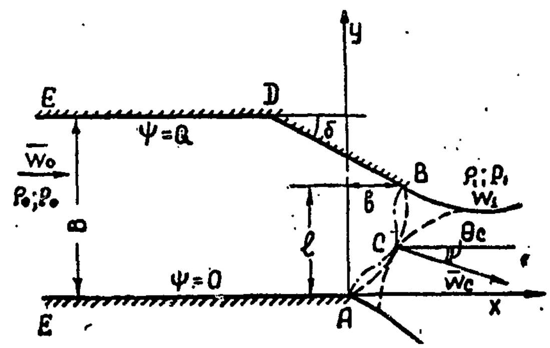

Fig. 1. Vessel used in the investigation

By solving the resulting boundary-value problem in a mixed region of subsonic and supersonic velocities, the effect of the asymmetry of the walls on the angle of deviation of the flow from its initial direction can be explained. If the shape of the vessel is known, the volume flow rate of the gas and the angle of inclination of the flow at the center of the nozzle can be determined. It was found that a relatively small asymmetry of the vessel (17%) produced a jet deviation of 30°. Therefore, control surfaces placed in the exhaust nozzle of jet engines are highly effective in controlling the direction of the exhaust stream.

2. Cherkez, A. Ya. Certain characteristics of supersonic flow in the initial section of a gas ejector. IN: Akademiya nauk SSSR. Izvestiya. Otdeleniye tekhnicheskikh nauk. Mekhanika i mashinostroyeniye, no. 6, 1962, 40-49.

A theoretical analysis is presented of the physical meaning of a number of flow peculiarities in the initial section of an ejector with supercritical pressure ratios of the mixing gases. Existing methods for determining the flow parameters in the mixing region are discussed, and an attempt is made to clarify the meaning of certain contradictory results. Optimal ejector parameters and the mixing-chamber shape are discussed. Conditions governing the size of the cross section of the supersonic jet in the choking section are determined. The initial region of a free jet with pressure higher than that of the surrounding medium is considered, and compatible solutions for continuity and momentum equations are analyzed. Forces acting on the walls of a supersonic nozzle of the primary flow are studied, and the rate of nozzle divergence at which the resultant force has the maximum possible value for the given initial gas parameters is determined. The problem of performance optimization is investigated. A nozzle in which static pressures of primary and secondary flows at the nozzle exit are equal is considered. The relationship between the ratio of the optimal and the designed exit cross sections of the nozzle and the reduced ejection coefficient is established and expressed graphically.

3. Makeyev, N. N. Collision of gas jets. Prikladnaya matematika i mekhanika, v. 26, no. 2, 1962, 308-315.

An exact solution is presented for the two-dimensional problem of the collision of gas jets flowing out of coaxial channels of finite width with parallel walls. By means of the theory of gas jets at subsonic velocities, the problem is reduced to a boundary-value problem for Chaplygin's equation, the solution of which is presented in the form of a Fourier series. S. A. Chaplygin (O gazovykh struyakh (Gas jets), Moscow-Leningrad, GITTL, 1949) proposed a method of solving the problems of subsonic jet flow for the case in which only one specific velocity is given. Chaplygin's method was improved by S. V. Fal'kovich (Theory of gas jets. PMM, 1957, v. 21, no. 4, 459-464) to permit the solution of problems with more than one specific velocity. This improvement makes possible the investigation of a number of problems of jet-collision theory which are of interest in improving the accuracy of a theory of shape charges developed in

a first approximation by M. A. Lavrent'yev (Shape charge and principles of its operation. UMN, 1957, v. 12, no. 4, 41-56).

4. Mezhirov, I. I. Calculation of one-dimensional gas flow in a variable-section duct in the presence of friction and heat exchange. Zhurnal prikladnoy mekhaniki i tekhnicheskoy fiziki, no. 3, 1962, 92-95.

The problem of calculating a one-dimensional gas flow in a duct with varying cross-section in the presence of friction forces and heat exchange between the gas and the external medium is investigated. The effect of these factors on the total gas pressure is studied, and the problem of determining the duct-section variation necessary to obtain the designated Mach-number distribution for a given heat-exchange law is solved. The variation in stagnation temperature required by a designated Mach-number distribution in a given duct form is also investigated. A numerical method is presented for calculating longitudinal Mach-number distribution along a duct of given form for a given heat-exchange law. All calculations are based on the assumption of one-dimensional gas flow. This assumption is widely used in applied gasdynamics, since it substantially simplifies the calculating methods and makes it possible to take into account quite complex external effects on the gas flow. The results of this investigation can be used in the solution of various critical problems encountered in gasdynamics and heat engineering.

5. Moiseyev, M. G. Gas discharge from a Laval nozzle into a liquid. Inzhenerno-fizicheskiy zhurnal, v. 5, no. 9, 1962, 81-84.

The discharge of a gas at supersonic speeds (Mach. 1.73, 2.09, 2.58, and 3.00) from four Laval nozzles into a tank filled with water has been investigated at the Mechanical Engineering Institute, Leningrad. The height of the water above the center line of the nozzles was 300 mm. The throat diameter of all nozzles was 4 mm, and the expansion angle, 10°. Pressures in the jet were measured by an electrically heated Pitot tube. No influence of gravity on the discharge was detected. The emerging gas jet can be divided into two sections. The first section extends to a distance from the outlet equal to about 10 times the diameter of the nozzle and is characterized by pressure oscillations. In the second section the pressure decreases continuously. It was assumed that shock waves in the first section are the same as would occur in dis-

charge of the gas into air. The jet expansion angle was 18—25°. The boundary layer of the jet consists of a gas-liquid mixture moving at a velocity lower than that of the center of the jet. The pressure distributions measured can be described by $\Delta p/\Delta p_m = (1 - \xi^{1.5})^3$, where Δp and Δp_m are the gage pressures at a given point and on the axis of the jet, and $\xi = y/b$, where y is the distance from a given point to the jet axis and b is the radius of the jet.

6. Nesterov, Ye. D. Aerodynamic contraction of a gas stream. Izvestiya vysshikh uchebnykh zavedeniy. Aviatsionnaya tekhnika, no. 1, 1962, 82-91.

The interaction of two streams of a compressible fluid directed at an angle to each other has been investigated. The main flow of a gas is contracted by an injected flow supplied through an annular slot placed in the region of the minimum cross section of the main flow. The conditions of aerodynamic contraction are derived for a converging nozzle and a Laval nozzle. In the converging nozzle, the separation zone is open to the atmosphere; in the Laval nozzle the separation zone is a totally enclosed region. Interaction between the flows is considered for cases in which 1) the ratio of the total pressures corresponds to velocity coefficients of the injected flow below unity and 2) the flow rate of the injected flow is less than 6% of that of the main flow. The absence of heat exchange is assumed. One-dimensional analysis is applied, with the assumption that instantaneous mixing of the two flows occurs. It is further assumed that the injected flow expands to reach the static pressure of the main flow at injection angles between 90° and 180° and to the pressure of the partially decelerated flow at injection angles between zero and 90°. Equations for the convergent nozzle are established. Six equations are derived from the flow geometry, the condition of expansion of the injection flow, continuity, the momentum equation, the energy equation, and the relation between total pressures (with two variants, for cases with and without losses). The ratio of the two mass flows is introduced, as well as the gas constant and the ratio of specific heats for the mixture. The six equations so formulated have eight unknowns. The remaining two equations are furnished by the power characteristics of the generation of the main flow. Several variants are considered, namely: an induced-draft arrangement; a forced-draft arrangement with a centrifugal compressor having either constant or variable compressor speed; and finally, a forced-draft arrangement with an axial compressor having

a constant compressor speed. A similar approach can be used in analyzing the flow for ramjet or rocket engines with aerodynamic control. The effectiveness of aerodynamic control is judged by the specific contraction area, which is defined as the contraction of the main jet divided by the area of the injection slot. A fair agreement was found between the present theory and experimental data. Effective flow control with acceptable pressure losses can be achieved at an injection angle between 70° and 90°. Test results obtained by A. G. Zenukov (Izvestiya vysshikh uchebnykh zavedeniy. Aviatsionnaya tekhnika, no. 1, 1959) are compared with the present theory. In these experiments, the depth of penetration of the controlling flow was judged by the size of orifices which have the same effect as aerodynamic contractions. This effective contraction depth is compared with values obtained analytically in the present paper, with satisfactory agreement. A similar analysis is presented for the Laval nozzle, in which it is assumed that the "dead water" or separation zone does not extend beyond the cylindrical portion and maintains the same static pressure as that at the end of the cylindrical portion. In a numerical example, the specific contraction area is given as a function of the total pressure ratio of the controlling and main flows.

7) Nikol'skiy, A. A. Some unsteady gas flows and their steady hypersonic analogies. Inzhenernyy zhurnal, v. 2, no. 2, 1962, 246-253.

Theoretical investigations have been conducted of the approximate analogy between hypersonic steady gas flows, particularly flows in channels, and unsteady flow with fewer variables, when the direction of the velocity vector differs slightly from the fixed stream line direction anywhere in the flow. It is assumed that the analogy is sufficiently exact, even for local Mach numbers on the order of 3, and can be applied for an approximate plot of certain singular hypersonic flows in nozzles and diffusers. In the case of plane-parallel laminar steady flows, the analogy with unsteady flows is valid when the angle of the velocity vector deviates greatly. The investigation was carried out at the Institute of Mechanics of the Academy of Sciences, USSR, Moscow.

8) Pelevin, V. S. Effect of pressure on maximum temperature in the combustion zone and on the ignition temperature of a homogeneous mixture in a turbulent flow. Inzhenerno-fizicheskiy zhurnal, no. 3, 1963, 34-39.

The combustion of a homogeneous mixture of B-70 gasoline with air in a turbulent flow is studied at a constant Reynolds number and at pressures of 31,255—101,080 n/m^2, in a test assembly previously described by the author (Inzhenerno-fizicheskiy zhurnal, no. 6, 1962), to obtain relationships for the conditions of stable combustion, maximum combustion efficiency, and optimum combustion-chamber length for air-breathing engines at variable flight altitude. Processing of the experimental data shows that with decreasing pressure, the ignition temperature increases and the combustion temperature and combustion efficiency decrease. These changes are attributed to heat transfer from the combustion zone into the ignition zone. It is also shown that the ratio (M) of the temperature gradient (Δt) to the length (L_{com}) of the corresponding section of the combustion zone varies linearly with the combustion efficiency according to the relationship

$$M = (CO_2 \max - a)C.19,$$

where a is the % of CO_2 in the mixture. M has a maximum at the ignition point and a minimum at the point of maximum temperature. As the pressure decreases, temperature at the point corresponding to 1% CO_2 decreases from 1700° to 1173°. At an arbitrary point in the combustion zone, the following relationship is established for temperature as a function of pressure:

$$t_{CO_2} \sim p^{0.?}.$$

The results suggest that in order to increase combustion efficiency, secure stable combustion, and minimize the length of the combustion chamber at high flight altitudes, it is necessary to introduce an additional amount of heat, owing to the increased ignition temperature. This heat increase can be achieved by preheating the combustion mixture or by increasing the power of the ignition source. The amount of heat required can be evaluated from the temperature gradient and the length of the combustion zone element, determined experimentally for a given pressure. The heat required will vary with flight altitude. The study was conducted at the Power Engineering Institute imeni G. M. Krzhizhanovskiy, Moscow.

9) Repik, Ye. U., and Chekalin, V. Ye. Convective heat exchange in supersonic conical nozzles. Inzhenernyy zhurnal, v. 2, no. 2, 1962, 359-364.

An approximate method is proposed for calculation of the local values of convective heat transfer coefficients from the gas side of a nozzle wall. An experimental method for checking the results obtained is also discussed. Fig. 2 shows a device designed especially for use in this checking procedure and consisting of conic nozzles 300 mm long with a 1/3 diameter ratio. The device was operated at pressures of 4—5 kg/cm², temperatures of 697, 723, and 785°K, and a velocity of M 5 at the nozzle outlet.

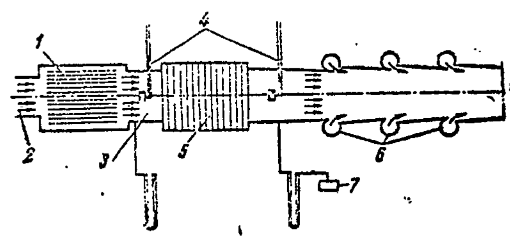

Fig. 2. Diagram of device used in the tests

1 - Baffle feed heater; 2 - compressed air; 3 - mixing chamber; 4 - thermocouples; 5 - test nozzle; 6 - system of ejectors; 7 - vacuum pump.

Determination of heat transfer coefficients is necessary for calculation of nozzle cooling. However, existing theoretical formulas were found to be unreliable, and experimental data are scanty and concern only subsonic nozzles. The method of calculation is based on splitting the wetted nozzle contour into a number of small sections, in each of which the flow is assumed to be nongradient. Continuous variation of the flow parameters is thus replaced by a stepped variation. A formula is given for calculation of N_r in every section; the heat transfer coefficient is determined at every point x as a function of the local values of N_r and M. The experimental method is based on direct measurement of the parameters of heat flux in the different sections. The nozzle is cooled by boiling water. Brass boxes containing copper coils through which water flows are placed at 24 different locations along the nozzle. Vapors of the boiling water condense on the coil surface. The amount of heat transferred from the nozzle section is determined by measuring the rate of flow of the water circulating through the coils and the temperature differential between the inflowing and outflowing water. The heat transfer coefficient is calculated from this temperature differential. The theoretical and experimental results were found to be in satisfactory agreement.

10) Timma, E. Turbulent round and plane gas jets in a countercurrent gas stream. IN: Akademiya nauk Estonskoy SSR. Izvestiya. Seriya fiziko-matematicheskikh i tekhnicheskikh nauk, v. 11, no. 4, 1962, 253-262.

The Power Institute, Estonian Academy of Sciences, has determined velocity and temperature profiles in round and plane gas jets at velocities of 13—20 m/sec, developed in a gas stream flowing countercurrently at a velocity of 6—7 m/sec. Experiments were conducted with both identical and different jet and gas-stream temperatures. Round and plane jets were generated in a circular nozzle 40 mm in diameter and in a rectangular nozzle 40 mm high and 200 mm wide, respectively. Processing of the radial and axial velocity profiles showed that the velocity profiles expressed by the dimensionless velocity parameters $f_k(\eta) = (U - U_n) / (U_m - U_n)$ (where U, U_n, and U_m are velocities at arbitrary points in the jet, the gas stream, and along the axis) are similar in the entrance and transition sections of the jet when $f_k(\eta)$ - 0.3—1. In concurrent jets the velocity profiles are similar and can be represented by this function in the entrance, transition, and main jet sections. The velocity and temperature profiles in the main section of countercurrent jets can be determined by a derived polynomial formula. Two formulas are given for determining the penetration range of round and plane countercurrent jets. The investigation was carried out under the guidance of Yu. V. Ivanov, Doctor of Technical Sciences, and is a continuation of earlier studies made by Kh. N. Suy and Yu. V. Ivanov (Investigation of the development of a round jet in the main part of a large-diameter countercurrent. Izvestiya AN ESSR. Seriya tekhnicheskikh i fiziko-matematicheskikh nauk, v. 8, no. 2, 1959) and Kh. N. Suy (Investigation of the development of a round and plane jet encountering a concurrent flow. Izvestiya. Seriya fiziko-matematicheskikh i tekhnicheskikh nauk, v. 10, no. 3, 1961). However, the earlier studies did not cover the entire length of the gas jet.

11) Yakovlevskiy, O. V. Mixing of jets in a channel of variable cross section. IN: Akademiya nauk SSSR. Izvestiya. Otdeleniye tekhnicheskikh nauk. Mekhanika i mashinostroyeniye, no. 1, 1962, 66-72.

An attempt is made to devise a method of analysis for a jet-type flow of fluid in a variable cross-section channel with a nonuniform velocity distribution. The problem is applicable to the mixing chambers of ejectors, double-flow jet engines and other gas-dynamic devices. Two zones

are present in the mixing of coaxial flows in a channel, a primary flow zone in which the dimension of the mixing region is smaller than the cross section of the channel, and a secondary zone in which the channel is filled out. The present analysis deals with the latter. The nondimensional velocity distribution retains a similarity along the length of the channel. This similarity is illustrated in graphs, obtained by the author and from other sources, of the velocity distribution across the section at various points along the channel. The Schlichting law derived for a free turbulent jet is assumed to hold inside the channel. This law is shown on the same graphs to represent adequately the experimental velocity distribution. In the analysis, the fluid is assumed to be incompressible, and the static pressure, uniform across the sections. Friction against the channel wall is neglected. The problem reduces to a determination of the velocity along the channel axis, the mean velocity, and the static pressure as functions of the length coordinate. The differential equation derived is found to be an Abel equation of the second kind. This equation can be integrated for the cases of cylindrical and conical channels. The variation of the peak velocity along the channel axis is shown in a graph for a cylinder and for straight-sided divergent and convergent cones, illustrating the well-known fact that the velocity profile evens out in a convergent nozzle. When the divergence reaches a certain value, the nonuniformity increases, since in this case the nonuniform deceleration becomes more powerful than the turbulent mixing process. Good agreement was found between the results of the present analysis and earlier experimental results. The present author's experiments with a convergent nozzle of about 8°, an outlet diameter of 100 mm, and a length of 1 m, in which two controllable air jets were mixed, are shown to be in good agreement with the theory.

12) Zysina-Molozhen, L. M. Calculation of the thermal boundary layer in the flow of a compressible gas. Inzhenerno-fizicheskiy zhurnal, no. 6, 1962, 21-26.

A semiempirical approximation method is proposed for calculating the laminar, transition, and turbulent regions of the thermal boundary layer during plane flow of a compressible gas past a round surface. The integral energy equation expressed in variables by Dorodnitsyn is transformed, and the flow parameters are included. The equation derived for the local heat-exchange coefficient is compared with the corresponding formula for incompressible flow. By relating all the physical constants to the stag-

nating temperature, T_0, a formal analogy is found between the formulas for the intensity of heat exchange in a compressible gas flow (Nu_x) and in an incompressible gas flow (Nu'_x). In the case where the velocity at the outer limit of the boundary layer equals the velocity of the incoming flow, $Nu_x = Nu'_x$, the results are in satisfactory agreement with experimental data. The data obtained by the author, together with that of other researchers, show that the r_x parameters characterizing the relation between the coordinates of the beginning and end points of the transition region are not dependent on the Mach number. It is therefore possible to determine r_x from empirical curves obtained for incompressible flow. The results are presented in 2 graphs. The research was carried out at the Central Boiler and Turbine Institute imeni I. I. Polzunov, Leningrad.

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